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Microwave-induced torrefaction of rice husk and sugarcane residues

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ABSTRACT

This study utilized microwave irradiation to induce torrefaction (mild pyrolysis) of rice husk and sugarcane residues by varying different parameters, including microwave power level, processing time, water content, and particle size of biomass. Proper microwave power levels are suggested to be set between 250 and 300 W for the torrefaction of these two agricultural residues. With proper processing time, the caloric value can increase 26% for rice husk and 57% for sugarcane residue. Compared to dry rice husk, both maximum reaction temperature and mass reduction ratio increased with higher water content (not over 10%). Moreover, the particle size of biomass needs not to be very small. The mass reduction ratios were 65 wt.%, 69 wt.%, and 72 wt.%, when the sizes were 50/100 mesh, 100/200 mesh, and >200 mesh, respectively. Microwave-induced torrefaction reduces more oxygen/carbon ratio of biomass in comparison with traditional torrefaction. Microwave-induced torrefaction is considered as an efficient and promising technology with great potential.

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1. Introduction

Biomass fuels can provide more environmental advantages in comparison with fossil fuels or other types of alternative energy. It is considered to be a clean and abundant future energy. During the growth of the biomass materials, the amount of carbon dioxide removed from atmosphere via photosynthesis can offset the emission of carbon dioxide due to combustion of biomass fuels [1]. Biomass materials can be converted into biomass fuels through physical, thermal, chemical, and biological technologies. The thermal technologies such as direct combustion, pyrolysis, and gasification are the most common used methods [2]. Besides, bioenergy is the only one kind of alternative energy which can supply the fuels in liquid, gas and solid phases [3]. Among them, the solid-phase fuel can be produced through torrefaction process [4].

Torrefaction process is one of the thermal treatments and can be regarded as a pretreatment process before combustion and gasification. Furthermore, it is a so-called mild pyrolysis process. Similar to pyrolysis process, torrefaction takes place in an inert atmosphere, but the temperature requirement is not as high as pyrolysis process (usually at temperature above 400–500 °C), while being suggested to set between 200 and 300 °C, and the heating rate of torrefaction has to be less than 50 °C/min. Untreated biomass materials are known for disadvantages such as high water content, low energy density, difficulty in comminuting into small particles, expensive transportation, and thermal instability resulted from high oxygen/carbon (O/C) ratio [5]. However, torrefaction helps remove water content and low-molecular-weight organic volatiles and can also decompose long polysaccharide chains of biomass materials. Through above-mentioned reactions caused by torrefaction, biomass materials can be converted into high quality fuels with low water content, low O/C ratio, and high energy density [4].

There has been much literature about the torrefaction of biomass in these two decades. Most of the studies used electric heating, so-called conventional heating method, as the heating source. Moreover, in those studies, the effects on the properties of torrefied biomass by various processing temperature and processing time were discussed [6–10]. In conventional heating processes, energy is transferred to the material through conduction, convection, and radiation of heat from the outside to the inside of materials. In addition to commonly used heating sources, microwave irradiation provides an alternative heating method. There are three types of interaction between materials and microwave irradiation, which are reflective (conductors), transparent (insulators) and absorptive (dielectrics) reactions. Therefore, not all materials can be heated by using microwaves. However, specific materials that have dielectric properties can be heated by microwave energy delivered directly to materials through molecular interaction within the electromagnetic field. Therefore, microwaves produce heat by converting electromagnetic energy to thermal energy instead of

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Table 1
The proximate, ultimate and heating values analyses of biomass feedstock.

	Proximate analysis (wt.%)					Ultimate analysis (wt.%)			
	Moisture	Volatile matter	Fixed carbon	Ash	Caloric value (MJ/kg)	C	H	O	N
Rice husk	6.44	80.45	8.60	10.95	17.4	44.04	6.55	43.94	0.24
Sugarcane residue	9.73	93.60	3.65	2.5	17.8	49.19	6.94	40.45	0.43

heat transferring. Because of the difference in how heat being generated; microwave heating has many potential advantages in processing materials. Microwave heating is a selective, rapid, uniform, and energy-saving method without direct contacts with the heated materials [11]. Therefore, it is widely used in many applications including synthesis [12], digestion [13], extraction [14], sample pretreatment [15], stabilization [16–19], etc.

The goal of this research is to study the microwave effects on the torrefaction of rice husk and sugarcane residues, and to analyze the characteristics of the solid products obtained from the torrefaction treatments. In order to compare different products obtained by torrefaction, different experimental conditions, including microwave power level, processing time, particle size and water content of biomass, are tested. Another aim of the research is to determine the optimal conditions that would be the most favorable for producing high quality fuels (torrefied char).

2. Methods

2.1. Materials

In Taiwan, the annual average of rice production was ca. 1.6 million tons in 2001–2005. The rice husk is generated about ca. 0.6 million tons annually after manufacturing of the grain. Besides, the sugarcane, tall tropical perennials of family Gramineae, plays an important role in agriculture of Taiwan. There is ca. 1 million tons of sugarcane residues left from refined sugar industry every year. Therefore, this study selected these two types of prevalent agricultural residues, rice husk and sugarcane residues, as the feedstocks for microwave-induced torrefaction tests. The rice husk was obtained from a rice mill factory in Changhua County in Taiwan, and the sugarcane residues were received in Nantou County in Taiwan.

The two typical agricultural residues, rice husk and sugarcane residue, were shred and sieved by 50/100 mesh (0.297 mm/0.149 mm). The residues were dried for 2 h at 105 °C before the experiments. Table 1 shows the proximate and ultimate analyses of the rice husk and sugarcane residues. The proximate and ultimate analyses were according to ASTM Standard Test Method D5142 and D5291, respectively.

After that, Thermal Gravimetric Analyses (TGA) was applied. The TGA curve can indicate the mass loss of sample with the increase of temperature. The TGA was done by using Shimadzu TGA-51. A platinum crucible loaded with around 7 mg of sample was heated from 25 °C to 800 °C with the heating rate of 20 °C/min in an inert environment (no oxygen). Nitrogen was used as a carrier gas with a flow rate of 200 cc (STP)/min.

2.2. Experimental device

In this study, a single-mode (focused) microwave device with 2.45 GHz frequency was applied, as shown in Fig. 1. The magnetron inside the microwave generator can convert electrical energy to microwave energy which can be adjusted from 0 to 2000 W, and then the microwave energy can be guided to reaction chamber. In the incident pathway, there is a 3-stub tuner in charge of regulating the incident angle of microwave to make sure that the peak of microwave is in the center of reaction zone. In the end of microwave pathway, a short circuit was set to adjust the wavelength phase of microwave. For every experimental batch at the beginning, adjusting the 3-stub tuner and short circuit properly can help minimize the reflection microwave and to prevent large amount of

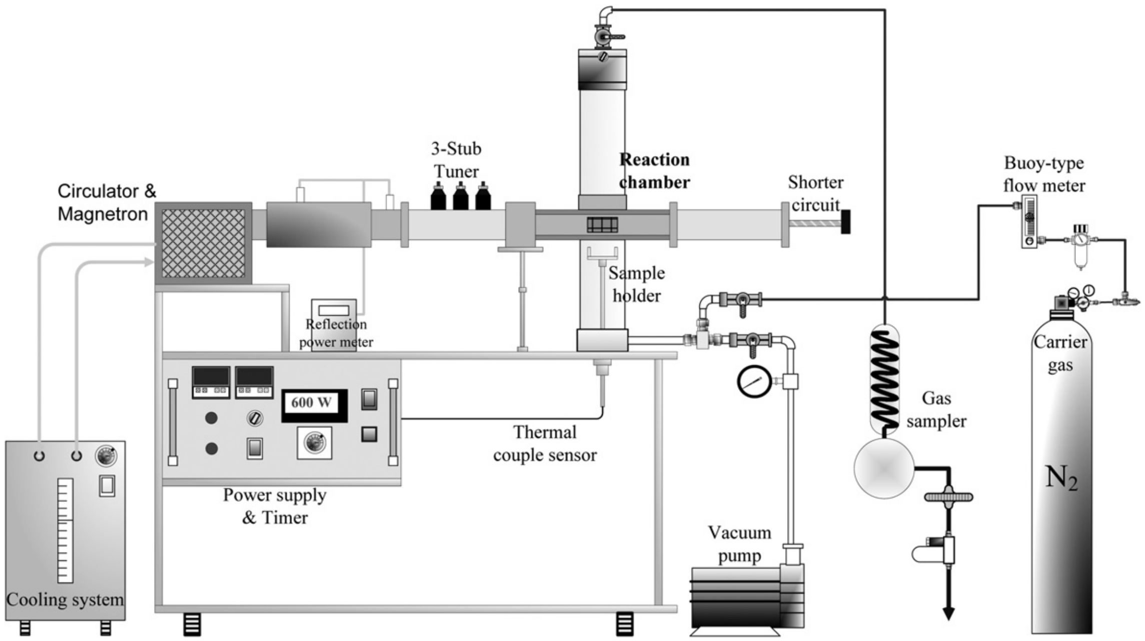

Fig. 1. The experimental apparatus.

radiation to the surroundings. The reaction tube (40 cm height, 5 cm outer diameter) and the sample holder (3 cm height, 4 cm outer diameter) which are both made of quartz were installed inside the reaction chamber. The cooling system was connected to the microwave device to prevent overheating during the experiment. The reaction temperature was measured by a thermocouple whose sensor was settled at the bottom of the sample holder.

2.3. Microwave-induced torrefaction procedure

The dried and sieved biomass of 7–10 g (precision to 0.1 mg) was filled in the sample holder. After the sample holder was placed in the pathway of microwave, the quartz tube was sealed tightly. In order to maintain anoxic circumstances, Nitrogen gas was purged into the system with a flow rate of 50 mL/min and controlled by buoy flow meter. After purging N_2 for 30 min, anoxic atmosphere can be reached. Then the microwave power was turned on to the designated microwave power level for the designated processing time. Reflection microwave power was adjusted to be below 10% of incident microwave power during the whole experimental period. After reaching the designated processing time, the microwave generator was shut down. The carrier gas kept purging until solid residues were cooled down to 80 °C before removing to desiccators. In this study, four parameters, including microwave power level, processing time, water content of biomass, and particle size were varied to optimize the process. The detailed operating conditions are depicted in Table 2.

2.4. Analytical methods

The caloric value of raw materials and torrefied solid residues were determined by CAL2 K ECO calorimeter. The elemental analysis was carried out by Elementar vario EL III analyzer. The TGA analysis was carried out by Shimadzu TGA-51.

3. Results and discussion

3.1. TGA results of rice husk and sugarcane residue

The TGA results of rice husk and sugarcane residues can be divided into three main stages for these two materials. In the first stage (below 250 °C), there were about 10% weight losses of rice husk and sugarcane residues due to the drying procedure and the removal of low-molecular-weight volatiles. However, there were more significant weight losses of rice husk and sugarcane residues observed in the second stage. When the temperature was between 250 and 550 °C, hemicellulose, cellulose and lignin were decomposed during this stage. Due to these decompositions, the weights of these two materials decreased for over 60%. When the temperature was beyond 550 °C (the third stage), the weight losses of these two materials were not as obvious as the previous stages. Weight losses of these two materials may be mainly due to the decomposition of some high-weighted components. The results obtained from TGA are consistent with past studies.

Table 2
The operating conditions for microwave-induced torrefaction.

Operating parameters	Conditions
Microwave power level	150 W, 200 W, 250 W, 300 W, 350 W, 400 W
Processing time	Adjust to microwave power
Water content	0%, 5%, 10%, 15%
Particle size	50/100 mesh, 100/200 mesh, >200 mesh

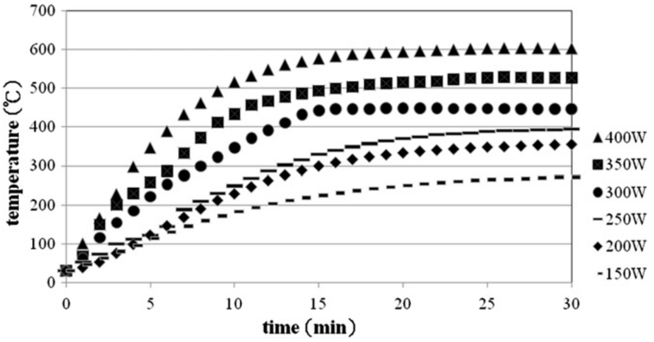

Fig. 2. The temperature profile of rice husk at different microwave power levels.

3.2. Effect of microwave power level on reaction temperature

This study adopted microwave energy as the heating source. Due to the selectivity of microwave heating method, the primary task is to test whether rice husk and sugarcane residues are proper dielectric materials or not. The microwave power level of 100 W was tried at the beginning, but the heating rate was only 10 °C/min and the final temperature merely reached 148 °C. Thus the torrefaction reaction cannot be completed thoroughly by 100 W microwave irradiations. The temperature profiles of rice husk and sugarcane residues at different microwave power levels are shown in Figs. 2 and 3, respectively.

In Fig. 2, for the first 5 min, heating rates of rice husk were among 17–50 °C/min and the final temperatures were distributed from 272 to 527 °C when the microwave power levels were between 150 and 350 W. Likewise, the heating rate reached 65 °C/min and the final temperature was 604 °C at 400 W. Most of the experiments reached their maximum temperatures in 15 min. Besides, higher microwave power levels can lead to both higher heating rate and final temperature. According to the results of rice husk torrefaction, 150–300 W microwave power and 15 min reaction time should be sufficient for the reaction. Thus the experiments of sugarcane residues torrefaction were operated at these conditions. In Fig. 3, for the first 5 min, the heating rates of sugarcane residues were between 16 and 78 °C/min and the final temperatures were between 179 and 573 °C when using the microwave power levels of 150–300 W. By comparing the results of sugarcane residues and rice husk, it shows that the sugarcane residues were easier to absorb the microwave radiation than rice husk at the microwave power level of 200 W and upward. This is coincident with the TGA results, which showed that the sugarcane residues lost weight earlier than rice husk did. Therefore, this may imply that the sugarcane residues are easier to be thermally degraded than rice husk.

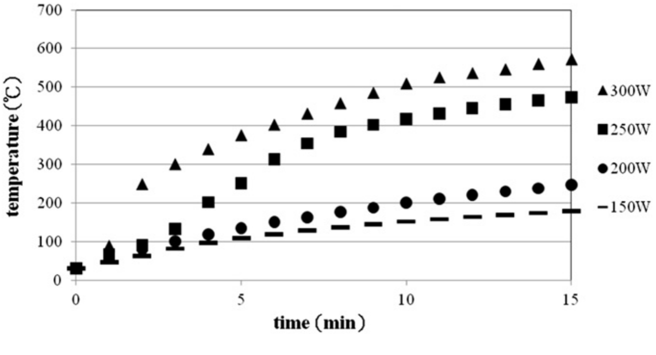

Fig. 3. The temperature profile of sugarcane residues at different microwave power levels.

Table 3
Experimental processing time with corresponding to final temperature conditions at certain microwave power levels.

Biomass	Microwave power	Processing time/final temperature
Rice husk	250 W	8 min/209 °C; 10 min/240 °C; 12 min/289 °C; 20 min/370 °C; 30 min/394 °C
	300 W	4 min/185 °C; 6 min/253 °C; 8 min/299 °C; 10 min/347 °C; 15 min/443 °C; 30 min/447 °C
	350 W	4 min/230 °C; 6 min/287 °C; 8 min/373 °C; 10 min/434 °C; 30 min/527 °C
Sugarcane residue	250 W	4 min/202 °C; 5 min/251 °C; 6 min/313 °C; 15 min/474 °C

3.3. *Effect of microwave power level and processing time on torrefaction*

According to the data from temperature profiles and the conditions of torrefaction (heating rate <50 °C/min), the conditions of microwave power level and processing time are listed in Table 3. The proper microwave power levels were 250 W, 300 W, and 350 W for rice husk and 250 W for sugarcane residues. All the samples were dried and sieved (50/100 mesh) in advance. Rice husk was taken by 10–12 g for each torrefaction experiment, and sugarcane residues were taken by 7–9 g.

Since the torrefaction of biomass can lead to mass reduction, the experimental results show that there was higher mass reduction ratio of biomass while applying higher microwave power levels. For example, the mass reduction ratios of rice husk torrefaction for 30 min were 66.63 wt.%, 67.72 wt.%, and 71.90 wt.% at 250 W, 300 W, and 350 W, respectively. The mass reduction ratios of sugarcane residues torrefaction for 15 min were 32.12 wt.%, 44.42 wt.%, 74.53 wt.%, and 77.76 wt.% at 150 W, 200 W, 250 W, and 300 W, respectively. The processing time also has effects on mass reduction ratio. For instance, the mass reduction ratios of rice husk torrefaction at 300 W were 50.55 wt.%, 63.51 wt.%, 63.72 wt.%, and 65.06 wt.% when the processing time was 4, 6, 8, and 10 min, respectively. The mass reduction ratios of sugarcane residues torrefaction at 250 W were 32.83 wt.%, 40.51 wt.%, and 67.10 wt.% when the processing time was 4, 5, and 6 min, respectively. Besides, the mass reduction ratios of rice husk torrefaction were 40.16 wt. %, 59.68 wt. %, and 63.43 wt. % when the reaction temperatures were 200, 250, and 300 °C, respectively. This phenomenon should be due to the carbonization and volatilization reactions of biomass which would take place at the same time during the process of torrefaction. At the higher reaction temperatures, volatilization reaction of biomass might become a predominant reaction during the torrefaction process. As a result, the mass of biomass would be reduced [10].

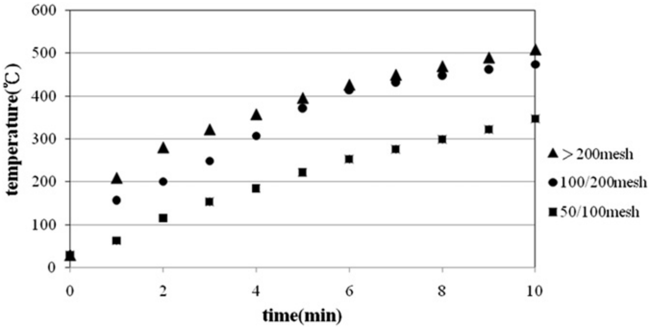

Fig. 4. The particle size effect on reaction temperature.

3.4. *Effect of particle size of biomass on reaction temperature*

The particle size of biomass would have a great effect on the efficiency of heat transfer of microwave-induced torrefaction. Fig. 4 shows the temperature profiles of three different particle sizes of rice husk, which were 50/100 mesh (0.149–0.297 mm), 100/200 mesh (0.149–0.074 mm) and >200 mesh (smaller than 0.074 mm) at 300 W for 10 min. The results indicate that both heating rate and reaction temperature increased when the particle size was shred to smaller size. Besides, the mass reduction ratios increased as well. The mass reduction ratios were 65 wt.%, 69 wt.%, and 72 wt.% when the particle sizes were 50/100 mesh, 100/200 mesh, and >200 mesh, respectively. The results might be attributed to higher bulk density and intraparticular contact area of the biomass in smaller particle size which would increase the efficiency of heat transfer during the torrefaction reaction. This may imply that the microwave

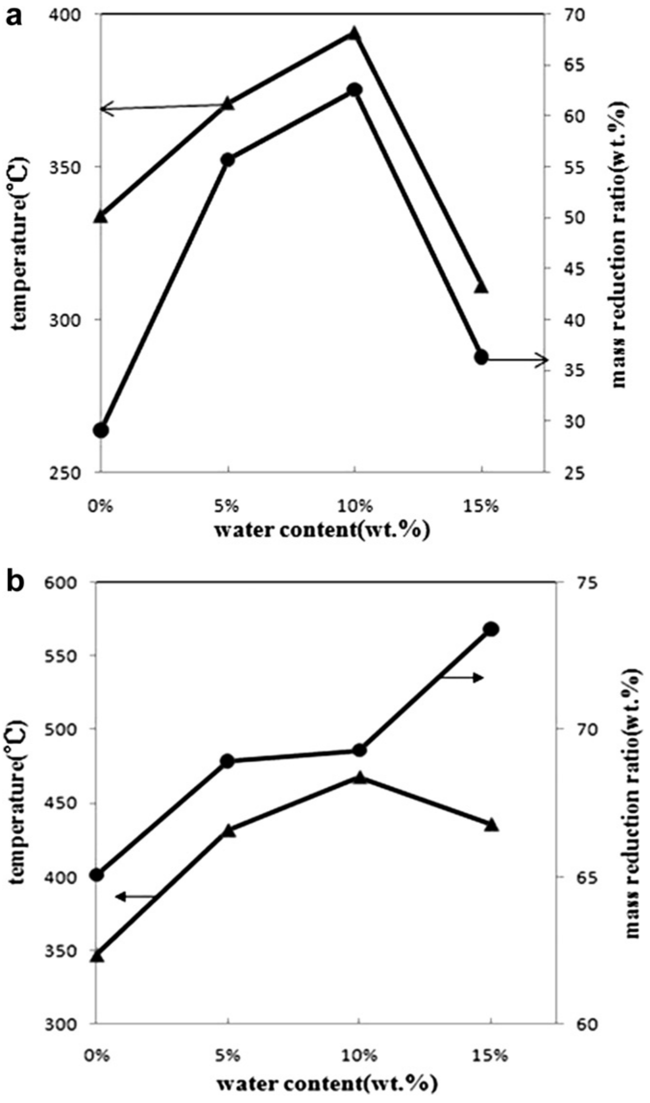

Fig. 5. Effect of water content on reaction temperature (▲) and mass reduction ratio (●) of rice husk torrefaction. (a) 200 W–20 min; (b) 300 W–10 min.

energy focuses on only one spot. Therefore, better heat transfer would accelerate the entire reaction of the smaller sample [20].

3.5. Effect of water content of biomass on reaction temperature

Because water is a polar molecule which has an electrical dipole, it can absorb microwave energy in a process called dielectric heating. Thus water can be regarded as a good microwave absorbent. When conducting experiments with different parameters (including microwave power level, processing time, and particle size of biomass), all the samples were dried in order to prevent the disturbance from the water molecules which can compete with biomass for absorbing microwaves. The water content in rice husk was varied by adding extra water (0%, 5%, 10%, and 15%), and the rice husk was torrefied at 200 W for 20 min and at 300 W for 10 min. The experimental data are shown in Fig. 5. The results demonstrate that the reaction temperature slightly increased in low water content (5% and 10%) of biomass at 200 W for 20 min but markedly increased at 300 W for 10 min. It is inferred that there are significant influences on different water content of biomass at higher microwave power levels. For lower water content of biomass, there was less water in biomass to promote the rice husk to absorb the microwave and to cause a rise in reaction temperature. On the contrary, there was a drop in reaction temperature when water content of biomass was higher. This may imply that the water molecules are converted from liquid phase into gas phase by absorbing microwave energy, and then the final reaction temperature decreases accordingly. Therefore, when the water content of biomass goes beyond a specific range, the reaction temperature will be declined.

With respect to the power level used for the mass reduction of rice husk with different water content, there were more significant effects of different water content of biomass on the mass reduction at lower microwave power level (200 W), while there were less significant effects at higher microwave power level (300 W).

3.6. Energy properties

Table 4 presents the properties of the torrefied solid products at various microwave power levels and processing time. As expected, the caloric values varied with different microwave power levels and processing time. An increase in microwave power level for the same processing time led to an increase in carbon content. By comparing solid products produced from rice husk torrefaction at 150–400 W microwave power levels for 30 min, the carbon contents of 50.45–51.22% (150–200 W) increased to 54.03–58.95% (250–400 W). Therefore, the carbon content can be increased by 8.5% when the microwave power level is 250 W or higher. Besides, in the range of 150–300 W for 30 min, the caloric values of solid products increased for 15–21%. However, when the microwave power levels were set between 350 and 400 W for 30 min, the caloric value just increased for 13–14%. This may be attributed to the torrefaction reaction removing the volatiles and decomposing the lignocelluloses of biomass. The higher content of carbon remained in the solid products gave a rise to the caloric value. However, higher microwave power levels lead to higher reaction temperature, which might cause partial carbon content to be pyrolyzed and thus produce solid products with lower caloric values. In the study of Huang et al. [20], when microwave power level was beyond 400 W, the fixed carbon content of solid products had a significant reduction in the caloric value. The reason may be that the fixed carbon would be also pyrolyzed by microwaves or it would undergo a secondary reaction with gas products.

Besides, with an increase in processing time at certain microwave power levels, there was a peak of caloric value for each microwave power level. For example, while rice husk was torrefied at 250 W for 20 min, 300 W for 15 min, and 350 W for 10 min, the caloric value of solid products increased for 22–26% during the process. However, after the specific processing time, the caloric value began to decline. Therefore, less processing time is needed when biomass torrefaction is at higher microwave power levels. This should be due to that higher microwave power levels

Table 4
The properties of the torrefied solid products.

Biomass	Torrefaction condition	Elemental analysis (wt.%)				H/C ratio	O/C ratio	Caloric value (MJ/kg)
		C	H	N	O			
Rice husk	Raw	44.04	6.55	0.24	49.17	0.15	1.12	17.4
	150 W–30 min	50.45	4.65	5.35	39.55	0.09	0.78	20.0
	200 W–30 min	51.22	5.46	0.36	42.96	0.11	0.84	20.0
	250 W–8 min	55.88	4.76	0.27	59.09	0.09	0.70	20.1
	250 W–10 min	58.55	4.26	0.29	36.90	0.07	0.63	20.6
	250 W–12 min	59.35	4.29	0.31	36.05	0.07	0.61	21.0
	250 W–20 min	61.44	2.49	5.54	30.53	0.04	0.50	21.8
	250 W–30 min	56.48	3.53	0.29	39.70	0.01	0.70	21.6
	300 W–4 min	53.05	4.92	0.24	41.79	0.09	0.79	20.2
	300 W–6 min	57.79	4.17	0.31	37.73	0.07	0.65	20.7
	300 W–8 min	58.34	3.74	0.31	37.61	0.06	0.64	21.1
	300 W–10 min	59.45	2.30	5.24	33.01	0.04	0.56	21.0
	300 W–30 min	58.95	4.27	0.30	36.48	0.07	0.62	21.1
	350 W–4 min	58.37	4.58	0.32	36.93	0.08	0.63	20.4
	350 W–6 min	59.82	4.06	0.29	35.83	0.07	0.60	20.8
	350 W–8 min	58.63	2.08	3.21	36.08	0.04	0.62	21.2
	350 W–10 min	60.46	2.06	3.07	34.41	0.03	0.57	21.9
	350 W–30 min	54.03	3.36	3.30	42.31	0.06	0.78	19.8
	400 W–30 min	57.22	4,87	0.24	37.67	0.09	0.66	19.7
Sugarcane residue	Raw	49.04	6.55	0.24	44.17	0.13	0.90	17.8
	250 W–4 min	55.93	5.45	5.25	33.37	0.10	0.60	21.0
	250 W–5 min	59.54	5.10	5.26	30.10	0.09	0.51	22.2
	250 W–6 min	61.34	5.26	5.45	27.95	0.09	0.46	25.9
	250 W–15 min	77.86	3.14	6.44	12.56	0.04	0.16	27.8
	250 W–20 min	76.85	2.23	6.76	14.16	0.03	0.18	27.8
	250 W–30 min	75.14	2.25	5.67	16.94	0.03	0.23	20.9

accelerate the torrefaction reaction. As for sugarcane residues, the caloric value increased for 57% at 250 W for 15 min, and the caloric value began to fall down after 15 min. It is inferred that reaction temperature would be higher with an increase in processing time. When the processing time was too long, the torrefaction would adversely go beyond expectation and end up with a reduction in the caloric value.

Furthermore, the energy yield of torrefied biomass is considered a useful assessment of the process and can be calculated from mass yield, as described by Bergman et al. [21]. The mass yield (η_{m}) and energy yield (η_{E}) calculations are shown in Eqs. (1) and (2), where m_{treated} = mass of treated biomass, m_{raw} = mass of untreated biomass, HHV = higher heating value:

$$\text{Mass yield}: \ \eta_{\mathrm{m}} = \frac{m_{\mathrm{treated}}}{m_{\mathrm{raw}}} \times 100 \tag{1}$$

$$\text{Energy yield}: \ \eta_{\mathrm{E}} = \eta_{\mathrm{m}} \times \frac{\mathrm{HHV}_{\mathrm{treated}}}{\mathrm{HHV}_{\mathrm{raw}}} \times 100 \tag{2}$$

The mass yield and energy yield of torrefied solid products at different operating conditions are shown in Table 5.

The results show that the mass yield and energy yield of rice husk and sugarcane residues were reduced with the increase of processing time at certain microwave power levels. For example, at 250 W, the mass yields of rice husk for 8, 10, 12, and 30 min were 39.71%, 38.18%, 37.28%, 33.62%, and 33.37%, and the energy yields were 46.00%, 45.36%, 44.99%, 42.25%, and 39.55%, respectively. Likewise, the mass yields of sugarcane residues for 4, 5, 6, and 15 min were 67.16%, 59.49%, 32.90%, and 25.47%, and the energy yields were 79.42%, 74.06%, 47.98%, and 39.87%, respectively. Therefore, it is inferred that neither high microwave power nor long reaction time is unnecessary. High energy yield (about 60% for rice husk and 80% for sugarcane residues) can be achieved when there are proper microwave power levels (250–300 W) and reaction time (<5 min). This also means that biomass torrefaction with mild microwave power level and controlled microwave irradiation time may meet high energy efficiency (e.g., the torrefaction of sugarcane residues at 250 W for 4 min). Besides, Deng et al. [10] selected rice straw and rape stalk as raw materials for torrefaction at 200, 250, and 300 °C for 30 min. The solid products retained 30–66% of the energy yields of the feedstock.

As for the smaller particle size of biomass, it is inferred that when the particles size is shred to be smaller, the heat transfer will be promoted more efficiently between particles. Thus the small particles decomposed more completely, and part of the carbon content was pyrolyzed as well. Therefore, the caloric value of solid products decreased with the reduction in particle size. For instance, the caloric values were 21.0, 20.4, and 16.9 MJ/kg when the particle sizes were 50/100 mesh, 100/200 mesh, and >200 mesh, respectively. It is inferred that before conducting the microwave-induced torrefaction reaction, biomass should be shred and sieve to a proper small size in order to homogenize the reaction.

As for the water content of biomass, the results show that at lower microwave power level (200 W) small amount of water (5% and 10%) in rice husk increased its caloric value up to 21–25%. The reason may be due to that the small amount of water existed in biomass makes the mass reduction of rice husk more significantly. Therefore, low-molecular-weight volatiles were removed and then the relative percentage of carbon content in biomass increased. While at higher microwave power level (300 W), the different water content of biomass did not have a significant effect on the caloric value. Thus this work also suggests that the drying pretreatment procedure would be unnecessary in the microwave-induced torrefaction since the water content of biomass would not have negative effect on torrefaction. Furthermore, the water content of biomass would increase the caloric value of the solid products at lower microwave power levels.

3.7. Elemental analysis

The elemental composition of biomass was changed after torrefaction. The O/C ratio can be considered an index for the continuous utilization of the torrefied solid products. Table 4 shows the results of elemental analyses of rice husk and sugarcane residues at different operating conditions. It shows that when torrefaction reaction took place, the carbon content of biomass increased along with the decrease in oxygen content, and the hydrogen content did not change a lot. There was peak value of carbon content of rice husk for each microwave power level of 250, 300, and 350 W and of sugarcane residues for 250 W for different processing time. This should be due to that the carbon was preserved after torrefaction. However, if the reaction temperature was too high, further carbon content would be decomposed. These results also agree with the results of caloric value analyses. It's worthwhile noting that the oxygen content of solid products decreased during the processes, and its spectrum of reducing oxygen was large in comparison with conventional torrefaction methods. Xiao et al. [22] mentioned that torrefaction reaction could reduce the oxygen content of the solid products indeed, but the range of reduction was limited. Zanzi et al. [23] studied five types of biomass (birch, salix, miscanthus, straw, and wood pellets) as the raw materials for conventional torrefaction, and after reaction, the O/C ratios were described as follows: from 0.73 (original) to 0.60 (reacted) for birch, from 0.84 to 0.75 for salix, from 0.85 to 0.60 for miscanthus, from 0.72 to 0.51 for straw, and from 0.69 to 0.55 for wood pellets at temperature of 280 °C for 3 h. While in this study, after microwave-induced torrefaction, the oxygen content of rice husk could be reduced from 49.17% to 36.05% at 250 W for 12 min

Table 5
Mass and energy yields for rice husk and sugarcane residues.

Biomass	Conditions	Mass yield (%)	Energy yield (%)	Conditions	Mass yield (%)	Energy yield (%)
Rice husk	250 W–8 min	39.71	46.00	300 W–10 min	34.94	42.33
	250 W–10 min	38.18	45.36	300 W–30 min	32.74	39.68
	250 W–12 min	37.28	44.99	350 W–4 min	36.13	43.01
	250 W–20 min	33.62	42.25	350 W–6 min	35.56	42.63
	250 W–30 min	33.37	39.55	350 W–8 min	34.86	42.53
	300 W–4 min	49.45	57.46	350 W–10 min	34.10	42.98
	300 W–6 min	36.49	43.41	350 W–30 min	28.10	32.00
	300 W–8 min	36.28	44.05			
Sugarcane residues	250 W–4 min	67.16	79.42			
	250 W–5 min	59.49	74.06			
	250 W–6 min	32.90	47.98			
	250 W–15 min	25.47	39.87			

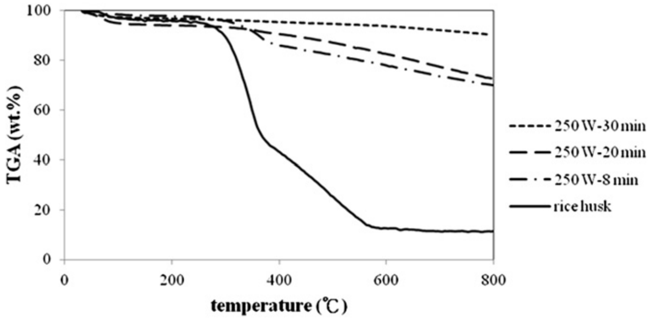

Fig. 6. The distributions of TGA of rice husk and torrefied solid products of rice husk.

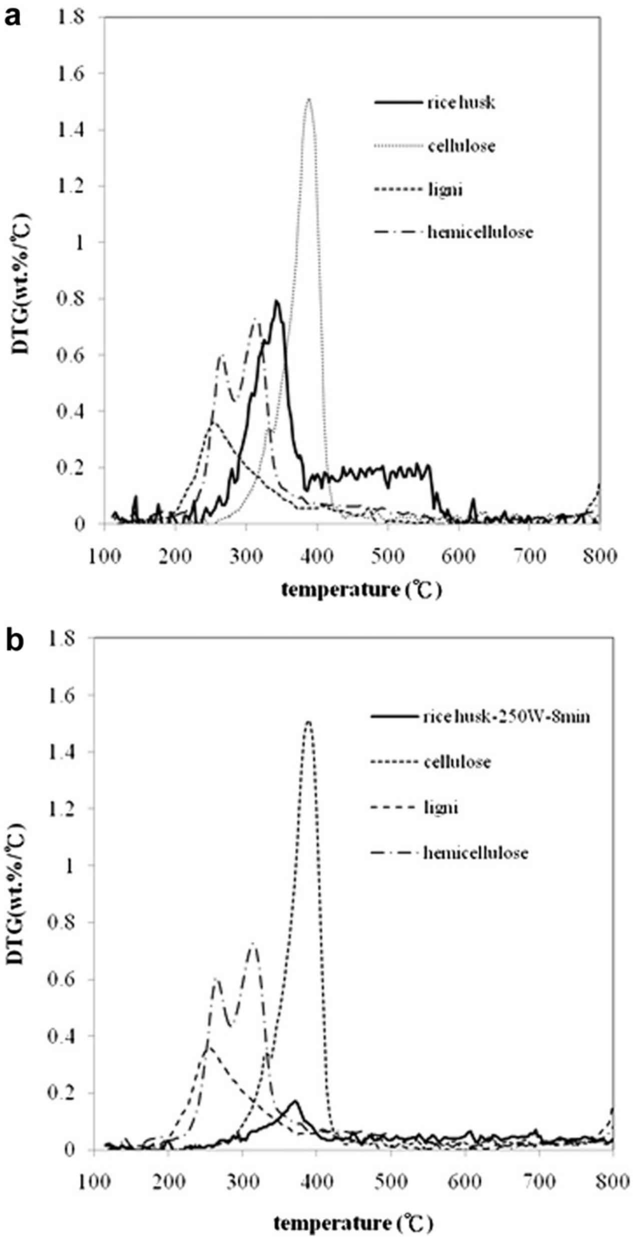

Fig. 7. The distributions of DTG of (a) rice husk and (b) torrefied solid product of rice husk.

(reaction temperature: 286 °C), and also of sugarcane resides from 44.17% to 30.10% at 250 W for 5 min (reaction temperature: 251 °C). Meanwhile, the O/C ratio declined from 1.12 to 0.61 for rice husk and from 0.90 to 0.51 for sugarcane residues. Therefore, microwave-induced torrefaction should be capable of being considered as an efficient and effective method to reduce the O/C ratio.

3.8. *TGA analysis*

TGA and DTG analyses can help figure out the difference between the raw materials and torrefied solid products. For example, the TGA and DTG results of rice husk and its torrefied solid products at 250 W for 8 min, 20 min, and 30 min are provided in Figs. 6 and 7. In Fig. 6, it can be found that the weight loss of rice husk were 89%, while after the torrefaction at the certain microwave (250 W) the weight loss of the solid products decreased with the increase of torrefaction processing time, such as 30% weight loss for 8 min, 27% weight loss for 20 min, and 9% weight loss for 30 min. It is inferred that the lignocelluloses of biomass are degraded during the torrefaction process. Besides, at certain microwave power levels, the reaction became more complete with the increase of processing time, which caused the decompositions of lignocelluloses more severely and the volatiles in biomass removed more. Consequently, there was a lower weight loss in TGA analysis. The DTG results of rice husk and its torrefied solid product are demonstrated in Fig. 7. The curve area of untreated rice husk in Fig. 7a is large, and it is obvious that there is a peak at temperature 342 °C which should stand for the thermal decomposition of cellulose, and the peak of hemicellulose overlaps that of cellulose at temperature 318 °C. The curve behind the peaks should come from the removal of lignin. In Fig. 7b, the curve for torrefied solid product of rice husk at 250 W for 8 min has a small covered area, and there is a peak at 366 °C supposed to represent for the thermal decomposition of cellulose. It is inferred that part of the cellulose and lignin remains and cannot be decomposed by the torrefaction process.

4. Conclusions

Microwave power level and processing time should be the primary parameters affecting the performance of microwave-induced torrefaction. The water content of biomass would not affect the reaction as much as other parameters at moderate microwave power. Proper microwave power levels are suggested to be set between 250 and 300 W, and the particle size of biomass is not required to be very small. Microwave-induced torrefaction can enhance the caloric value and also increase the carbon content while decrease the oxygen content of torrefied solid products efficiently and economically in comparison with conventional torrefaction.

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